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Ten years of conservation agriculture in a rice–maize rotation of Eastern Gangetic Plains of India: Yield trends, water productivity and economic profitability

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ABSTRACT

In recent years, scarcity of water, energy and labour, increasing production cost, decreasing farm profitability and climate-change-induced variability are major challenges faced by the farmers in the Indo-Gangetic Plains (IGP) of South Asia. Conservation agriculture (CA) based *best-bet* crop management practices may increase crop productivity and profitability, while conserving natural resources. In a 10-year (2007–2017) field study, we assessed the effects of four combinations of tillage and, crop establishment (TCE), and residue (R) management options for the crop and water productivity and profitability of rice-maize (RM) system in Eastern IGP of India. The treatments consisted of zero-till direct seeded rice followed by zero tilled maize (ZTDSR/ZTM); ZTDSR followed by maize both on permanent raised beds with residue (PBDSR/PBM (+R)); PBDSR followed by PBM without residue (PBDSR/PBM (-R)) and conventional till puddled transplanted rice followed by conventional till maize (PTR/CTM). Overall, mean rice grain yield was similar under ZTDSR/ZTM, PBDSR/PBM (+R) and PTR/CTM, but 5.0–7.9% higher than PBDSR/PBM (-R). However, the maize yield was significantly ($P < 0.05$) higher by 6–82% in CA-based PBDSR/PBM (+R) RM system compared to PTR/CTM and PBDSR/PBM (-R) right from first year onwards. The RM system productivity (rice equivalent yield, REY) was higher by 1.5–38% in CA-based systems [ZTDSR/ZTM; PBDSR/PBM (+R)] than in the PTR/CTM and PBDSR/PBM (-R) systems. APSIM model predicted yield of rice and maize under different TCE and residue management practices with cumulative probability distribution plots was higher and consistent in PBDSR/PBM (+R) and ZTDSR/ZTM compared to PBDSR/PBM (-R) and PTR/CTM, suggesting that CA plots has lower probability of low yield than CT. CA-based ZTDSR/ZTM and PBDSR/PBM (+R) practices reduced the total system water use by 151–341 mm and 212–423 mm, and resulted enhanced system water productivity (WP) by 27–57% and 39–68%, respectively compared to CT (PTR/CTM) system. Economic profit for RM system was always significantly ($P < 0.05$) higher (225–1028 US$/ha/year) in CA-based systems than in CT system. Our study shows that CA-based system under RM rotation is one of the ways for improving crop and water productivity and farm income, as well as sustaining the natural resources in smallholder production systems of Eastern IGP in India and other similar agro-ecologies of South Asia.

1. Introduction

The Indo-Gangetic Plain (IGP) of India, Bangladesh, Nepal and Pakistan, covering about 44 million hectares, is dominated by irrigated cereal-based cropping sequences, of which RM system occupies about 1.5 Mha (Timsina et al., 2010). Out of the 1.5 Mha under RM in South

Abbreviations: CA, conservation agriculture; CPD, cumulative probability distribution; CT, conventional tillage; IGP, Indo-Gangetic Plains; PB, permanent beds; REY, rice equivalent yield; RM, rice (*Oryza sativa* L.)-maize (*Zea mays* L.) system; TCE, tillage and crop establishment; WP, water productivity; ZT, zero tillage

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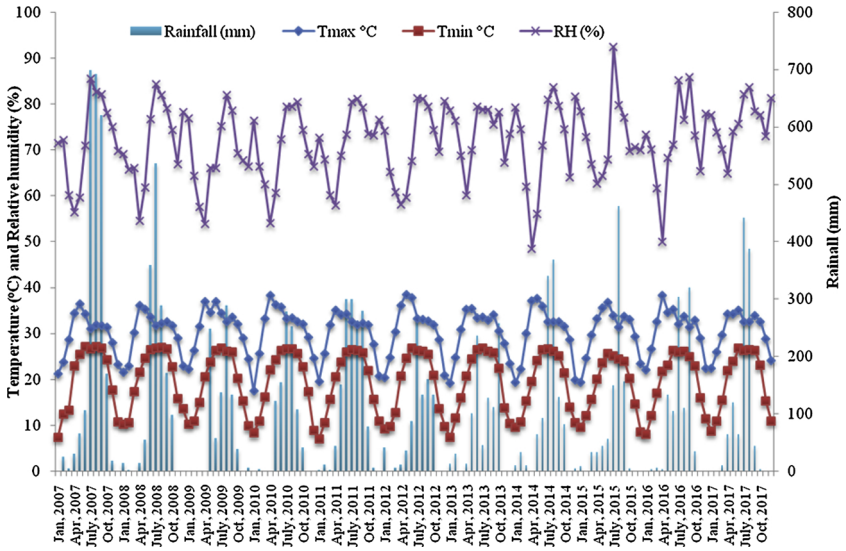

Fig. 1. The monthly minimum temperature (mean), maximum temperature (mean) and rainfall (total) during ten years study (2007–08 to 2016–17).

Asia, about 0.53 Mha are in India alone (Timsina et al., 2011). Maize is rapidly emerging as a favourable option for farmers in South Asia as a component crop in rice-based system. Drivers of such changes are higher productivity and profitability of maize. Winter maize consumes less water than the boro rice (Krupnik et al., 2017) due to which winter maize is viewed as a promising mitigation option of the arsenic (As) toxicity problem in the Gangetic regions of West Bengal and Bangladesh (Ravenscroft et al., 2005). Conventional crop management practices of cereal-based systems entail high production costs, depletion and/or degradation of natural resources (water, soil, biodiversity), low input-use efficiency (especially water, energy, fertilizers, pesticides, labour), environmental pollution (soil, water, air) in the IGP of South Asia (Humphreys et al., 2010; Saharawat et al., 2010; Jat et al., 2014). As compared to western IGP of India, the input: output scenario and productivity situation is worse in Eastern IGP, which may be attributed to high small farm holding, poor market infrastructure, less access to new technologies and frequent climatic aberrations (floods, droughts and heat stress) (Jat et al., 2014). In this primarily rain dependent ecology, conventional system of rice planting involves intensive dry and wet tillage followed by manual transplanting of seedlings often delays the rice transplanting causing yield reduction. Moreover, these intensive tillage operations in rice are not only labour, water, time, energy and carbon inefficient but also deteriorative for soil quality leading to 8–9% reduction in succeeding cereal crop yield compared to that grown after dry direct seeded rice (Kumar and Ladha, 2011). Positive results from the several studies on rice-wheat and rice-maize (RM) systems in north-western India (Gathala et al., 2011a; b; Jat et al., 2013) suggest that alternate tillage and crop establishment methods may also help in addressing the challenges of conventional tillage in rice–maize production system in Eastern India. Experimental evidence from various production environments in north-eastern IGP of India suggests that conservation agriculture (CA)-based management can have both immediate, e.g. reduced production costs, stabilized crop yield, improved WP (Bhushan et al., 2007; Hobbs, 2007; Parihar et al., 2017b) and long-term benefits, e.g. higher soil organic matter contents and improved soil quality (Gathala et al., 2011b; Parihar et al., 2016a). RM system with CA based management practices could help in enhancing the system productivity (Gathala et al., 2015), sustaining soil health and environmental quality (Singh et al., 2016), and saving irrigation water and labour costs (Parihar et al., 2017b).

CA-based soil and residue management coupled with crop diversification creates favourable soil environment for crop establishment and also during other physiological and phenological stages. However, most efforts in Eastern IGP revolved around zero tillage in wheat and on a small scale in legumes mainly in a commodity centric approach and the potential benefits of CA-based management have not been realized in most production systems including RM system (Gathala et al., 2015, 2016). Hence, there exists a large knowledge gap on the performance of CA -based practices in RM system.

Considering these facts, the present study was conducted to investigate the impact of CA technologies (ZT with residue retention and PB with and without residue retention) on the performance of RM cropping system in the eastern IGP. The objectives of our study were: (i) to evaluate the long-term (10-year) impacts of CA-based practices on crop yield and above-ground biomass productivity (net primary productivity), water productivity and economic returns in a RM system, (ii) to predict long-term sustainability of RM system under different CA-based practices using APSIM model. We hypothesized that ZT with bed planting and residue retention would result in higher crop productivity with less risk of lower yield, system water productivity and net returns compared with farmers' practice.

2. Material and methods

2.1. Description of experimental site and climatic conditions

A long-term (10-year) field experiment was conducted from 2007 to 2017 with a set of tillage and crop establishment (TCE) and residue management treatments in irrigated RM cropping system at the research farm of Dr. Rajendra Prasad Central Agricultural University, Samastipur, Bihar, India (25.58, 51 °N, 85.4°, 313E). The climate of the site is characterized by hot and humid summers and cold winters with an average yearly rainfall of 1344 mm, 70% of which is received between July to September (Fig. 1). Yearly rainfall of the cropping cycles (June to May) ranged from 787 to 2390 mm. The mean monthly minimum temperature ranged from 7.0 to 10.3 °C in January and mean monthly maximum temperature ranged from 33.5 to 38.5 °C in May-June. The monthly mean pan evaporation was 3.4–4.5 and 2.8–4.4 mm for monsoon and winter season, respectively. Mean values of rainfall and, minimum and maximum temperatures and relative humidity recorded at the experimental farm during monsoon (June–October) and winter (November-May) seasons are presented in Fig. 1. Soil sub-samples were collected at the start of experiment in May 2007 from 0 to 15 cm layer using steel auger of 5.0 cm internal diameter. The soil of experimental site was clay loam in texture, with pH (1:2 soil: water) 8.3, Walkley-Black carbon content (0.62%), 0.5 M $NaHCO_3$ extractable

Table 1
Description of tillage, crop establishment (TCE) and residue management practices under rice-maize system during nine years of experimentation.

S. No.	Used treatment notations	Tillage		Crop establishment		Residue management	
		Rice	Maize	Rice	Maize	Rice	Maize
1	ZTDSR/ZTM	Zero tillage	Zero tillage	Direct dry seeding on flat soil,row geometry	Direct drilling onflat soiland row geometry	50% rice crop residues retained in maize cycle	25% maize crop residues retainedin rice cycle
2	PBDSR/PBM(+R)	Zero tillage permanentbeds	Zero tillage permanent beds	Direct drilling onbedsand row geometry	Direct drilling onbedsand row geometry	50% rice crop residues retained in maize cycle	25% maize crop residues retained in rice cycle
3	PBDSR/PBM(-R)	Zero tillage permanent beds	Zero tillage permanent beds	Direct drilling onbedsand row geometry	Direct drilling onbedsand row geometry	All removed	All removed
4	PTR/CTM	Puddled transplanted rice sown with 3 passes of dry tillage with harrow, 2 passesof cultivator in ponded water	Conventional till maize sown with 2 passes of harrow, 1 pass of cultivator followed by 1 planking	Manually transplanted, random geometry	Drilling on conventional till flat soiland row geometry	All removed	All removed

P 13.7 mg/kg (Olsen et al., 1954), and exchangeable K 62.4 mg/kg (Prasad, 1998).

2.2. Experiment treatments and design

Four treatment combinations of TCE and residue management practices [zero-till direct seeded rice followed by zero tilled maize (ZTDSR/ZTM); ZTDSR followed by maize both on permanent raised beds with residue (PBDSR/PBM (+R)-CA based PB); PBDSR followed by PBM without residue PBDSR/PBM (-R)-mixture of CA and CT) and conventional till puddled transplanted rice followed by conventional till maize (PTR/CTM) (Table 1)] in a RM cropping system were tested. In 2007-08, rice residues (2.5 Mg/ha, dry weight basis) were applied in maize. In the subsequent years, about 3.1–4.8 and 2.8–5.0 Mg/ha, of rice residues were retained in ZTM and PBM treatments on soil surface in maize plots and maize residue of 2.2–5.0 and 2.6–5.0 Mg/ha were retained in ZTDSR and PBDSR plots of rice, respectively, and the remaining amounts of residues were removed for use as fodder for cattle. The experimental site was under rice-wheat cropping system for more than twenty years before the initiation of experiment in 2007. The experiment was conducted in large plots, each measuring 600 m^2 and replicated four times.

2.3. Crop establishment

2.3.1. Crop geometry

Before the start of the experiment, the field was deep tilled (to 30 cm depth) using a chisel plough to break the hard pan below the plough layer, followed by laser leveling. For transplanted rice, 25 days old seedlings were transplanted manually with random geometry with 30 seedlings m^{-2}. In PBDSR, 2 rows (30 cm apart) of rice were directly drilled on each raised beds (10–12 cm height) having 37 cm wide top and 67 cm furrow to furrow spacing using a multi-crop raised bed planter (A.S.S. Foundry & Agri. Works, Jandiala Guru, Punjab, India make ridge former), and no reshaping was done during rice cycle. In ZTDSR, rice seeds were directly drilled at 20 cm row spacing using zero tillage seed-cum-fertilizer planter having inclined-plate seed metering system (A.S.S. Foundry &Agri. Works, Jandiala Guru, Punjab, India). For all the DSR treatments, the seeding depth was maintained at 2–3 cm using depth control wheel of the planter. Conventional till maize was established after two ploughing with disc harrow followed by one pass of spring-tine cultivator through multi-crop planter (A.S.S. Foundry & Agri. Works, Jandiala Guru, Punjab, India). In ZTM plots, the crop was established without any preparatory tillage using zero-till seed-cum-fertilizer planter having inclined-plate seed metering system. The seeding depth was kept 3–5 cm using the depth control wheel. In PBM, one row of maize (67 cm apart) were established on each permanent raised bed using a raised bed planter. During the maize cycle, the raised beds were reshaped using reshaping shovel of the raised bed planter in one-go, i.e. seeding and reshaping operations together.

2.3.2. Seed rate, sowing time and cultivars

Rice crop was sown with seed rate of 12 kg/ha, 20 kg seed/ha and 25 kg/ha under transplanted, PBDSR and ZTDSR treatments, respectively. Winter maize was sown with a uniform seed rate of 25 kg seed/ha in all the treatments. Irrespective of the treatments, rice hybrid Arize 6444 was planted in 2013 and 2014, and long duration variety (Rajendra Mashuri) was used in the other years of study. The maize variety 30V92 (2007-08), Proagro Sampann (2008-09 and 2009-10), NK 6607 (2010-11), 900 M Gold (2011-12 and 2012-13), DKC 9120 (2013-14) and DKC 9081 (2014-15, 2015-16 and 2016-17), were grown. During all the study years, the rice and maize crops were sown in mid-June and mid-November and were harvested in the first fortnight of November and second fortnight of May, respectively.

2.4. Fertilizer and weed management

Monsoon rice received a common fertilizer dose of 150 kg N + 26 kg P + 17.5 kg K/ha and winter maize was fertilized with 200 kg N + 35 kg P + 26 kg K/ha. In both the seasons, 11% N and whole P, K and 10 kg Zn /ha were applied as basal using di-ammonium phosphate, murate of potash and zinc sulphate hepta hydrate with seed-cum-fertilizer drill, while remaining N was top dressed as urea in two equal splits at tillering and panicle initiation in rice and at V_5 and V_T growth phases in maize. Application of Zn fertilizer was made in alternate years.

For managing weeds, in permanent beds and zero-till plots, prior to seeding of rice and maize weeds were killed using pre-plant application of glyphosate 1.25 L a.i. per hectare but no herbicides were applied in conventionally tilled plots before seeding. The weed in the experimental plots were controlled by using pre-emergence as well as post-emergence herbicides as and when required but when applied, it was applied in all the treatments. The herbicides used for weed control in rice were: pendimethalin (1.0 L a.i./ha) as pre-emergence, ethoxysulfuron (18 g a.i./ha) and bispyribac sodium (25 g a.i./ha) as post-emergence. In maize, combinations of 2, 4-D (500 g a.i./ha) and Atrazine (1000 g a.i./ha) was used as post-emergence as per the need depending on the intensity and diversity of weed species.

2.5. Water application, measurement, and water productivity computations

Direct drilling of DSR was done by utilizing the soil moisture from pre-monsoon showers and consequently the DSR plots were irrigated only when no rainfall occurred for 10 consecutive days after seeding. As the experimental site is located in good rainfall area, both DSR and PTR plots were irrigated at the same time depending on rainfall events. The total number of irrigations applied to rice ranged from 3 to 8 depending upon the amount and distribution of rainfall in different years. In each irrigation, 8–10 cm water was applied to rice. The maize crop was generally drilled utilizing residual moisture after rice cycle in all treatments. Irrigation water in maize was applied based on critical crop growth stages. The number of post-sowing irrigations (6–7 cm each) in maize during different years varied from 7 to 9 depending on the winter rains. The amount of irrigation water was measured using a parshall flume (3″) installed in the main open channel. The total water input was calculated by adding the irrigation water and effective rainfall. Amount of rainfall was recorded using a manual rain gauge installed at the meteorological observatory adjacent to experimental field. The effective rainfall was calculated by using Cropwat 8.0 by USDA SCS method. Cropwat is a widely used computer based decision support tool developed by the Food and Agriculture Organization (FAO) to estimate effective rainfall based on climate and soil data. The total water input (irrigation + effective rainfall) and water productivity (kg grains/ ha-mm) were computed using equation (2.1) given by Bhushan et al. (2007).

Total water productivity = Grain yield (kg/ha)/Total water input (ha-mm) (2.1)

2.6. Data recording and measurement of yield

The data on crop management inputs such as number of tillage, fuel consumption, number of irrigations, herbicide, fertilizer, seed rate, labour use, pesticide application and their costs under each treatment were recorded for each crop using a standard data recording format. The rice crop was harvested manually from 3 randomly selected quadrates (from whole net plot area of 2x5 m^2) and maize crop in permanent raised beds was harvested from 3 beds (0.67X3 = 2.01m width) of 5 m length and in CT and ZT it was harvested from whole net plot area of 2x5 m^2) and mean grain yield was recorded.

To compare the productivity of RM system, the yield of maize crop was converted into rice equivalent yield (Mg/ha) by using the equation (2.2).

$$\text{Rice equivalent yield (Mg/ha)} = \frac{\text{Maize yield (Mg/ha) x minimum support price of maize (INR/Mg)}}{\text{Minimum support price of rice (INR/Mg)}} \quad (2.2)$$

2.7. Labour and machinery use

Labour was used for handling of machinery and farm equipments, and field operations such as tillage, layout, seeding, irrigation, application of fertilizer, insecticides and pesticide, weeding, watch and ward, harvesting and threshing. As per the labour commission of Government of India, manual labour use for 8-hours was considered equivalent to one person day. The time taken for tractor–drawn machines/implements to complete a field operation like tillage, seeding, fertilizer and pesticide application and harvesting was recorded and expressed as h/ha.

2.8. Economic analysis

The net returns from the production system were calculated over variable cost of production only.

2.9. Statistical and seasonal analysis

Analysis of variance (ANOVA) for completely randomized block design was performed using the general linear model procedures of the statistical analysis system (SAS Institute, Cary, NC) for completely randomized block design. The differences between treatment means were compared using a LSD test at $P < 0.05$ (Gomez and Gomez, 1984).

2.10. Simulation of rice and maize grain yield using APSIM

Cumulative probability distribution (CPD) for yields of rice, maize and RM system during 10-year study was done using the agricultural production systems simulator (APSIM) model (Keating et al., 2003). APSIM is a simulation modelling framework that enables sub-models to be linked to simulate agricultural system performance (Keating et al., 2003; Holzworth et al., 2014). The sub-models include modules for crops (e.g. ORYZA, MAIZE), soil water (SOILWAT), soil nitrogen (SOILN) and surface residue (SURFACE ORGANIC MATTER). The crop modules simulate. Descriptions of the modules can be found elsewhere (Keating et al., 2003). The MAIZE module is based on CERES Maize (Carberry et al., 1989; Muchow, 1989) and rice crop module (ORYZA) is based on rice crop physiology adapted from the ORYZA2000 model (Bouman and van Laar, 2006). We followed a robust three step process for experimental dataset to ensure best possible model configuration, before compiling and conducting the final evaluation statistics on model performance. These 3-steps were: parameterisation, calibration and validation (Gaydon et al., 2018). The validated model was used to simulate grain yield of rice and maize crops gown under different TCE and residue management practices over a 10-year period. The trend analysis was done by simple linear regression.

3. Results

3.1. Weather

The rainfall pattern of the experimental site was relatively variable during the ten years of study. This reflects rainfall uncertainty in the Eastern IGP and hence climate resilient management practices are very

vital for sustainable production and food security. The rainfall during monsoon season (June–October) was highest (1453 mm) in 2008 followed by 1211 mm in 2011 and 1012 mm in 2014, whereas 2009, 2010, 2012, 2013, 2015, 2016 and 2017 seasons received the lowest amount of rainfall (656–941 mm). The three months from June to September alone accounted for 54–82% of the total yearly rainfall received during the study years (Fig. 1). The rainfall in winter season (November to May) was very low (100–156 mm) during all the years except 2008-09, 2010-11 and 2016-17, whereas 248, 212 and 193 mm rainfall was received, respectively. The mean monthly minimum and maximum temperatures during rice season were almost similar in all the years. The range of mean monthly maximum and minimum temperature during monsoon season was between 30–38 and 20–27 °C, respectively. Likewise, the mean monthly maximum and minimum temperatures during maize growing season were comparable in all the years ranging between 17–39 and 7–25 °C, respectively (Fig. 1).

3.2. Yield

3.2.1. Grain yield of rice

ANOVA showed significant treatment effects of the tillage, crop establishment and residue management on 10-year (2008–2017) pooled rice grain yield (Table 2). The data pooled over ten years showed that grain yield of rice was significantly ($P < 0.05$) higher by 7.9%, 5.4% and 5.0% under ZTDSR, PBDSR (+R) and PTR, compared to PBDSR (-R), respectively. However, ZTDSR yielded at par with PTR (Table 2). The time trend analysis of grain yield showed an increase in rice slope yield with time in all the treatments. However, the increment rate was the highest in PBDSR/PBM (+R) (0.26 Mg/ha/year) followed by PTR (0.24 Mg/ha/year) and ZTDSR (0.22 Mg/ha/year) and lowest in PBDSR (-R) (0.13 Mg/ha/year) (Table 2). Accordingly the relative yield was significantly different in all the years (Fig. 2). The APSIM model simulations also support the differences in rice yield across the ten years of experimentation in various TCE and residue management practices. There was generally good agreement between simulated and observed accumulation of rice grain yield under different TCE and residue management practices (Fig. 3). Which followed similar trend in our study for simulated rice grain yields were i.e. 5.70 (S.E ± 0.16), 5.84 (S.E ± 0.16), 5.32 (S.E ± 0.13), and 5.60 (S.E ± 0.15) Mg/ha in ZTDSR, PBDSR (+R), PBDSR (-R) and PTR treatments, respectively (Fig. 3). The probability distributions for crop grain yields (Fig. 4) show that PBDSR (+R) and ZTDSR compared to the PTR potentially produce more yield. In 50% of years, PBDSR (-R), ZTDSR and PBDSR (+R) exceeded PTR yields by 0.24, 0.31 and 0.43 Mg/ha respectively (Fig. 4).

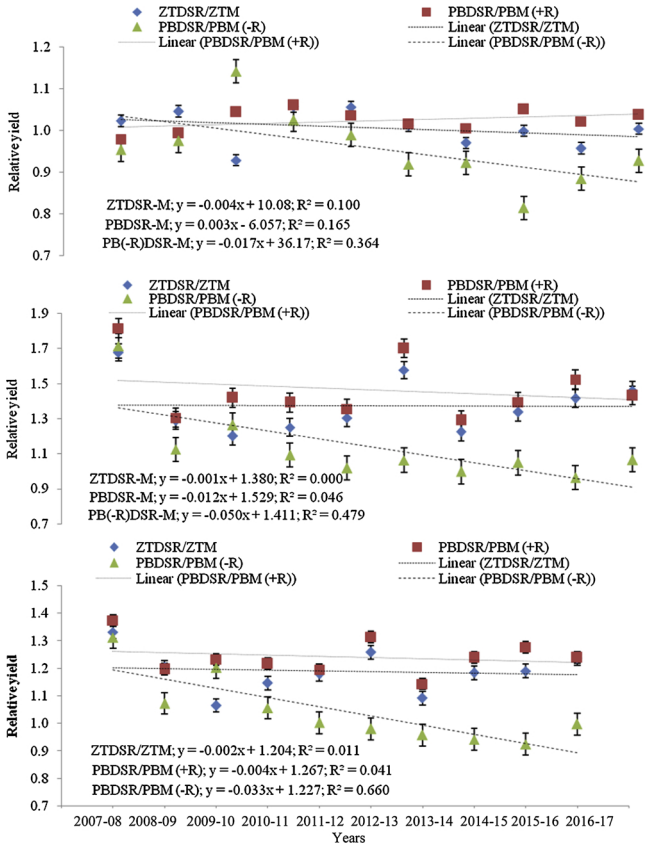
ZTDSR/ZTM
PBDSR/PBM (-R)
Linear (PBDSR/PBM (+R))
PBDSR/PBM (+R)
Linear (ZTDSR/ZTM)
Linear (PBDSR/PBM (-R))
Relative yield
ZTDSR-M; y = -0.004x + 10.08; R² = 0.100
PBDSR-M; y = 0.003x - 6.057; R² = 0.165
PB(-R)DSR-M; y = -0.017x + 36.17; R² = 0.364
ZTDSR-M; y = -0.001x + 1.380; R² = 0.000
PBDSR-M; y = -0.012x + 1.529; R² = 0.046
PB(-R)DSR-M; y = -0.050x + 1.411; R² = 0.479
ZTDSR/ZTM; y = -0.002x + 1.204; R² = 0.011
PBDSR/PBM (+R); y = -0.004x + 1.267; R² = 0.041
PBDSR/PBM (-R); y = -0.033x + 1.227; R² = 0.660
2007-08 2008-09 2009-10 2010-11 2011-12 2012-13 2013-14 2014-15 2015-16 2016-17
Years

Fig. 2. Trend in relative yield of rice, maize and system grain yield over time under different tillage and residue management practices.

3.2.2. Winter maize grain yield

The TCE methods and residue management practices had significant effects on maize grain yield in all the years of experimentation (Table 2). Results showed that grain yield of winter maize were significantly ($P < 0.05$) higher in PBM (+R), ZTM and PBM (-R), compared with CTM. However, maize planted in ZTM and PBM (-R), yielded at par (grain yield) during 2007-08 and 2009-10. In all the segregated ten years, the grain yield of maize with PBM (+R)/ZTM increased by 6–61% compared to PBM (-R) and CTM, respectively (Table 2). The time trend analysis of maize grain yield showed the

Table 2
Grain yield of rice and maize and rice-maize system productivity (Mg/ha) along with their trend over time as affected by different TCE and residue management practices in north-eastern India.

Treatments*	2007-08	2008-09	2009-10	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	10-year pooled	Slope LR#	R^2
Monsoon rice													
ZTDSR/ZTM	4.3	4.4^{a}	5.1^{d}	5.7	6.2	6.5	6.4^{ab}	6.0^{b}	5.9^{ab}	6.4^{b}	5.7^{ab}	0.22	0.68
PBDSR/PBM(+R)	4.1	4.2^{b}	5.8^{b}	5.7	6.1	6.5	6.6^{a}	6.3^{a}	6.3^{a}	6.7^{a}	5.8^{a}	0.26	0.73
PBDSR/PBM(-R)	4.0	4.1^{b}	6.3^{a}	5.5	5.8	5.9	6.1^{b}	4.9^{c}	5.5^{b}	6.0^{c}	5.4^{c}	0.13	0.24
PTR/CTM	4.2	4.3^{b}	5.5^{c}	5.4	5.9	6.4	6.6^{a}	6.0^{b}	6.2^{a}	6.4^{b}	5.7^{b}	0.24	0.73
Winter maize													
ZTDSR/ZTM	5.1^{b}	9.2^{b}	6.9^{b}	6.7^{b}	7.9^{b}	7.6^{b}	7.6^{b}	10.0^{b}	9.4^{b}	10.0^{a}	8.0^{b}	0.38	0.53
PBDSR/PBM(+R)	5.5^{a}	9.3^{a}	8.1^{a}	7.5^{a}	8.2^{a}	8.2^{a}	8.0^{a}	10.4^{a}	10.1^{a}	9.8^{a}	8.5^{a}	0.35	0.52
PBDSR/PBM(-R)	5.2^{b}	8.0^{c}	7.3^{b}	5.9^{c}	6.1^{c}	5.1^{c}	6.2^{c}	7.8^{c}	6.4^{c}	7.3^{b}	6.5^{c}	0.06	0.03
PTR/CTM	3.0^{d}	7.2^{d}	5.7^{c}	5.4^{d}	6.0^{c}	4.8^{c}	6.2^{c}	7.5^{c}	6.6^{c}	6.9^{c}	5.9^{d}	0.25	0.33
Rice-maize system													
ZTDSR/ZTM	10.7^{b}	14.8^{a}	11.9^{b}	11.6^{b}	13.9^{a}	14.4^{a}	13.9^{b}	15.7^{b}	15.0^{b}	16.2^{a}	13.8^{b}	0.47	0.60
PBDSR/PBM(+R)	11.0^{a}	14.7^{a}	13.7^{a}	12.3^{a}	14.1^{a}	15.1^{a}	14.6^{a}	16.5^{a}	16.1^{a}	16.2^{a}	14.4^{a}	0.47	0.67
PBDSR/PBM(-R)	10.5^{b}	13.2^{b}	13.4^{a}	10.7^{c}	11.8^{b}	11.2^{b}	12.2^{d}	12.5^{d}	11.7^{d}	13.0^{b}	12.0^{c}	0.07	0.04
PTR/CTM	8.0^{c}	12.3^{c}	11.1^{c}	10.1^{d}	11.8^{b}	11.5^{b}	12.8^{c}	13.3^{c}	12.6^{c}	13.1^{b}	11.7^{d}	0.40	0.57

* See Table 1 for treatment details, Means followed by a similar lowercase letter within a column are not significantly different (at $P < 0.05$) according to Least significant difference test.

\# Linear regression.

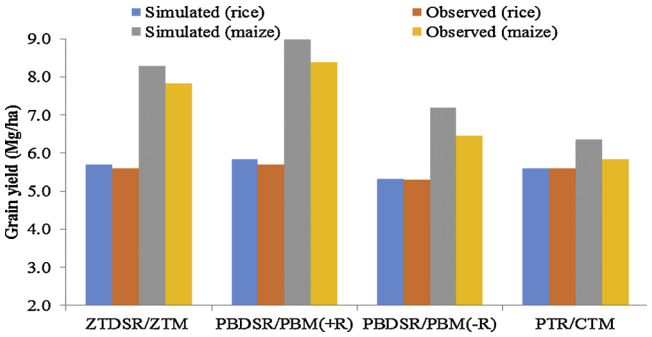

Fig. 3. APSIM simulated *vs* observed rice and maize grain yields (dry) under different tillage and residue management practices.

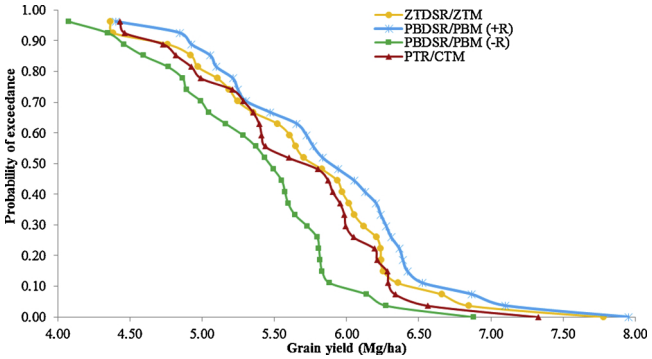

Fig. 4. Exceedance probability for rice yield data simulated over 27-years (1991–2017) under different tillage and residue management practices.

smallest increment in yield over years in PBM (-R) system (0.06 Mg/ha/year) and the highest increment (0.38 Mg/ha/year) in ZTM followed by (0.35 Mg/ha/year) in PBM (+R) (Table 2). The maize relative yield was significantly different in PBM (-R), PBM (+R) and ZTM in all the 10-year of the study and it was highest under PBM (+R) in first 9-years and with ZTM in the tenth year (Fig. 2). A total of 4 simulations were created with various TCE and residue management practices (Fig. 3). The study results also followed the similar trend for long-term simulated maize grain yield i.e. 8.29 (S.E ± 0.13), 8.98 (S.E ± 0.11), 7.18 (S.E ± 0.13) and 6.35 (S.E ± 0.19) Mg/ha in ZTM, PBM (+R), PBM (-R) and CTM treatments, respectively (Fig. 3). Potential grain yield was strongly affected by TCE, and residue management practices and potential yield ranged from 4.09 to 9.04 Mg/ha over the 27 years. In 50% of years, PBM (-R), ZTM and PBM (+R) exceeded CTM maize yields by 0.72, 1.81and 2.56 Mg/ha respectively (Fig. 5).

3.2.3. System grain yield

Based on the ten years' segregated data, system productivity (rice equivalent yield, REY) was significantly ($P < 0.05$) affected by TCE and residue management practices (Table 2). The REY ranged from 8.0 to 16.5 Mg/ha across different treatments and study years (Table 2). Across the experimentation years, the highest REY was recorded under PBDSR/PBM (+R), whereas this system yielded at par with ZTDSR/ZTM in 2nd, 5th, 6th and 10th year of the study and PBDSR/PBM (+R) system also yielded at par with PBDSR/PBM (-R) during 3rd year. The CA-based PBDSR/PBM (+R) plots increased ten years' segregated system productivity by 2.4–38.1% and 14.3–37.4% compared to PBDSR/PBM (-R) and PTR/CTM systems, respectively. The REY of RM registered significant improvement with residue retention in PBDSR/PBM (+R) and ZTDSR/ZTM plots compared to permanent raised beds without residue (PBDSR/PBM (-R)) and conventional till PTR/CTM plots in all the years of the study. However, conventional till PTR/CTM system gave minimum REY in first four years, while this treatment was second lowest (after PBDSR/PBM (-R)) in 7th, 8th and 9th years of

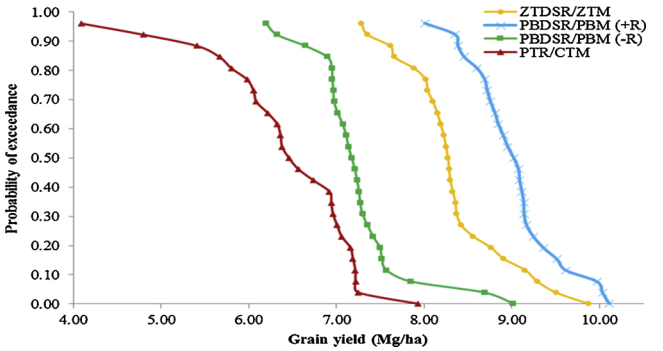

Fig. 5. Exceedance probability for maize yield data simulated over 27-years (1991–2017) under different tillage and residue management practices.

study. Both PBDSR/PBM (-R)) and PTR/CTM systems showed at par REY for 5th, 6th and 10th year (Table 2). The time trend analysis of system grain yield (REY) showed an increase in REY with time in all the treatments. However, the average increment rate was highest in PBDSR/PBM (+R)/ZTDSR/ZTM (0.47 Mg/ha/year) followed by PTR/CTM (0.40 Mg/ha/year). The increment in REY over years was the lowest under PBDSR/PBM (-R) system (0.07 Mg/ha/year) (Table 2). The relative system grain yield (REY) was significantly different in PBDSR/PBM (-R), PBDSR/PBM (+R) and ZTDSR/ZTM in all years during the 10-year study and it was significantly higher under PBDSR/PBM (+R) over ZTDSR/ZTM and PBDSR/PBM (-R) (except in 2008-09) (Fig.2). The 10-year predicted RM system yield under different TCE and residue management practices with CPD plots at 0.5, was followed the trend of: PBDSR/PBM (+R) < ZTDSR/ZTM < PBDSR/PBM (-R) < PTR/CTM. At 60% CPD level the system yield reduced by 18.8 and 18.1% in PTR/CTM and PBDSR/PBM (-R) plots compared to CA based PBDSR/PBM (+R), respectively. However the reduction in system yield was 3.5% in ZTDSR/ZTM plots compared to CA based PBDSR/PBM (+R). Similar trend for predicted RM system yield under different TCE and residue management practices was observed even at 90% CPD level (Fig. 5). This suggests that there is high probability for higher and sustainable RM system yields in long-term under CA based PBDSR/PBM (+R) and ZTDSR/ZTM plots, in contrast to PTR/CTM could be the risky TCE practice.

3.3. System water-use and water productivity

The amount of total water input (irrigation + effective rainfall) for all the TCE and residue management practices in the RM system was significantly higher by 15.0–21.8%, 10.6–17.9% and 15.0–21.8% in conventional till PTR/CTM plots compared to CA-based PB (PBDSR/PBM(+R)) and ZT (ZTDSR/ZTM) and partial CA-based systems (PBDSR/PBM(-R)) in all the years of the study, respectively (Table 3). TCE and residue management practices in the RM system invariably reduced the amount of water applied in all the years. For instance, PBDSR/PBM (+R) and PBDSR/PBM (-R) plots received 61–112 mm less water than ZTDSR/ZTM, and CA-based PBDSR/PBM (+R); PBDSR/PBM (-R) and ZTDSR/ZTM received 212–423 and 151–341 mm less water than PTR/CTM plots, respectively. Among the different TCE and residue management practices, PBDSR/PBM (+R); PBDSR/PBM (-R) received least amount of water (1143–1799 ha-mm), while PTR/CTM system received maximum (1373–2222 ha-mm) for all the years of study. The RM system water productivity (SWP) varied significantly among TCE and residue management practices (Table 3). Significantly ($P < 0.05$) higher SWP was observed in CA-based TCE than under PTR/CTM plots.

3.4. Economics

In all the years, cost of cultivation of RM system was significantly

Table 3
Ten years total water [irrigation (IW) + effective rainfall (ER)] input and system water productivity of rice-maize cropping system as affected by TCE and residue management practices in north-eastern India.

Treatments*	Total input water (IW + ER) ha mm										System water productivity (kg/ha-mm)									
	2007 −08	2008 −09	2009 −10	2010 −11	2011 −12	2012 −13	2013 −14	2014 −15	2015 −16	2016 −17	2007 −08	2008 −09	2009 −10	2010 −11	2011 −12	2012 −13	2013 −14	2014 −15	2015 −16	2016 −17
Tillage practices																				
ZTDSR/ZTM	1787^{c}	1880^{c}	1528^{c}	1621^{c}	1679^{c}	1402^{c}	1348^{c}	1268^{c}	1214^{c}	1486^{b}	6.0^{b}	7.9^{b}	7.8^{c}	7.2^{b}	8.3^{b}	10.3^{b}	10.3^{b}	12.4^{b}	12.4^{b}	10.9^{b}
PBDSR/PBM(+R)	1726^{c}	1799^{c}	1456^{c}	1560^{c}	1618^{c}	1341^{c}	1287^{c}	1207^{c}	1143^{c}	1375^{d}	6.4^{a}	8.2^{a}	9.4^{a}	7.9^{a}	8.7^{a}	11.2^{a}	11.3^{a}	13.6^{a}	14.1^{a}	11.8^{a}
PBDSR/PBM(-R)	1726^{c}	1799^{c}	1456^{c}	1560^{c}	1618^{c}	1341^{c}	1287^{c}	1207^{c}	1143^{c}	1375^{c}	6.1^{c}	7.3^{c}	9.2^{b}	6.9^{c}	7.3^{c}	8.4^{c}	9.5^{c}	10.4^{c}	10.2^{c}	9.5^{c}
PTR/CTM	2113^{a}	2222^{a}	1861^{a}	1947^{a}	2005^{a}	1623^{a}	1569^{a}	1419^{a}	1373^{a}	1716^{a}	3.8^{d}	5.5^{d}	6.0^{d}	5.2^{d}	5.9^{d}	7.1^{d}	8.1^{d}	9.4^{d}	9.2^{c}	7.6^{d}
Yearly total and effective rainfall trend (mm)																				
Monsoon total rainfall[#]	2287	1453	656	833	1211	786	778	1012	827	874										
Winter total rainfall[#]	103	248	131	212	100	156	117	123	144	193										
Yearly total rainfall	2390	1701	787	1044	1311	942	894	1136	972	1067										
Monsoon ER	788	701	455	546	681	556	533	574	457	524										
Winter ER	97	150	107	172	95	138	108	117	116	164										
Yearly ER	885	850	562	718	776	694	641	690	573	688										

* See Table 1 for treatment details, Means followed by a similar lowercase letter within a column are not significantly different (at P < 0.05) according to Least significant difference test.
# Mean monthly Tmax.,Tmin., RH and Rainfall.

higher in all the CT plots (1080–1728 US$/ha) and residue retained plots (PB/ZT) (937–1462 US$/ha) as compared to plots of PB without residue retention (922–1294 US$/ha). TCE and residue management practices had significant (P < 0.05) effect on net return of RM system in all the years of study (Table 4). Net returns were maximum in CA-based PB followed by CA-based ZT and CT + CA-based PB-R plots. The significantly lowest net returns were observed in PTR/CTM plots for all the years of study (154–1412 US$ ha). The time trend analysis showed incremental rate in the system net returns over years in all treatments but the rate of increase was the smallest in PBDSR/PBM (-R) (Table 4 and Fig. 6). The CA-based ZTDSR/ZTM and PBDSR/PBM (+R) had similar trend of increment in net returns, i.e. 138–140 US$/ha/year (Table 4 and Fig. 6). In general, conventional RM system had the intermediate net return 515 US$/ha/year in all the years of study.

4. Discussion

4.1. Crop yields

The results of this study clearly show benefits of going from flats to permanent RM system with residue retention. Results from our long-term study of higher rice yield in ZT and PB + R, RM system compared to PTR are in agreement with findings of other researchers in case of rice-wheat system (Kumar and Ladha, 2011; Gathala et al., 2011a) in the region. Contrary to the results from our study in silt loam soils, Sudhir-Yadav et al. (2011) and Bhushan et al. (2007) found similar performance of PTR and DSR on a clay loam and silt loam soils. The probable reasons for inconsistent results under two cropping systems may be attributed to better weed control, reduced percolation losses of water and nutrients, quick seedlings establishment and improved nutrient availability owing to puddling in PTR conditions. Further, variable rainfall pattern in the studied region, could also contribute to discrepancies in yield observed for the above treatments (Sharma et al., 2003; Gathala et al., 2011a). Over time, we changed the rice varieties to fit well with DSR and also used suitable herbicides for effective weed control (see Section 2) and other crop management practices to make CA-based system cost effective, productive and sustainable. Adopting ZT with residue retention (ZTDSR/ZTM) under RM system increased rice, maize and system yield by 0.01 (S.E ± 0.08), 2.10 (S.E ± 0.22) and 2.15 (S.E ± 0.25) Mg/ha/year compared to conventional RM system (PTR/CTM), respectively (Table 5). ZT in maize is the initial step towards adoption of CA-based management in RM system to facilitate early planting of maize where rice is harvested late and also reducing production cost (Gathala et al., 2015) yet giving yield advantage in both crops in the RM system.

The higher yield responses of CA practices were more in maize than in rice (Table 2 and Fig. 2). As a system, the benefits of ZT and residue retention were clear, right from first year and these benefits continued increase over time (Table 2 and Fig. 2). In our study, eliminating wet tillage (puddling) in rice had significant yield benefit (0.60 Mg/ha/year) on subsequent maize (Table 5) probably due to better germination and elongated rooting of maize due to improved soil physical properties. Consistent with the results from our study, Gathala et al., (2011b), also found higher yield of wheat by eliminating puddling in rice under rice-wheat rotation. Puddling induced soil compaction and poor soil aggregation have been found to adversely affect the rooting pattern of maize (Kumar and Ladha, 2011; Gathala et al., 2011b) leading to yield reduction in maize (Tables 2 and 5). Results from our study indicated that, PB system resulted in increasing trend in yields over time; 0.14 Mg/ha/year in rice and 2.59 Mg/ha/year in maize and 2.77 Mg/ha/year in RM system productivity (Table 5). ZT in combination with residue retention substantially increased the rice and maize yields thereby enhancing system productivity by 1.78 Mg/ha/year. Apparently, retention of crop residue in CA-based PB system increased rice, maize and RM rotation productivity by 0.42 (S.E ± 0.17), 1.99 (S.E ± 0.33) and 2.40 (S.E ± 0.45) Mg/ha/year, respectively over PB

Table 4
Ten years trend in economics of rice-maize cropping system under different TCE and residue management practices in north-eastern India.

Treatments*	2007 −08	2008 −09	2009 −10	2010 −11	2011 −12	2012 −13	2013 −14	2014 −15	2015 −16	2016 −17	Slope LR# (*US$/ha*)	R^2
Variable cost of cultivation (US$/ha)												
ZTDSR/ZTM	975[b]	1123[b]	1221[c]	1298[b]	1371[b]	1375[b]	1424[b]	1359[b]	1327[b]	1462[b]	–	–
PBDSR/PBM(+R)	937[c]	1069[c]	1246[b]	1279[b]	1330[c]	1350[b]	1392[c]	1355[b]	1340[b]	1418[c]	–	–
PBDSR/PBM(-R)	922[d]	1021[d]	1238[bc]	1202[c]	1228[d]	1177[c]	1288[d]	1187[c]	1150[c]	1294[d]	–	–
PTR/CTM	1180[a]	1325[a]	1522[a]	1558[a]	1602[a]	1539[a]	1719[a]	1610[a]	1574[a]	1728[a]	–	–
Net returns over variable cost (US$/ha)@												
ZTDSR/ZTM	772[b]	1418[a]	1533[b]	1693[b]	1979[a]	1999[b]	1796[b]	2192[b]	2089[b]	2384[a]	138	0.82
PBDSR/PBM(+R)	858[a]	1447[a]	1926[a]	1878[a]	2063[a]	2172[a]	1976[a]	2363[a]	2324[a]	2435[a]	140	0.78
PBDSR/PBM(-R)	799[b]	1250[b]	1909[a]	1566[c]	1641[b]	1469[c]	1556[c]	1658[c]	1544[c]	1849[b]	61	0.34
PTR/CTM	154[c]	807[c]	1107[c]	1058[d]	1251[c]	1136[d]	1227[d]	1397[d]	1319[d]	1412[c]	102	0.68

@ INR/US$ exchange rate.

* See Table 1 for treatment details, Means followed by a similar lowercase letter within a column are not significantly different (at $P < 0.05$) according to Least significant difference test.

Linear regression.

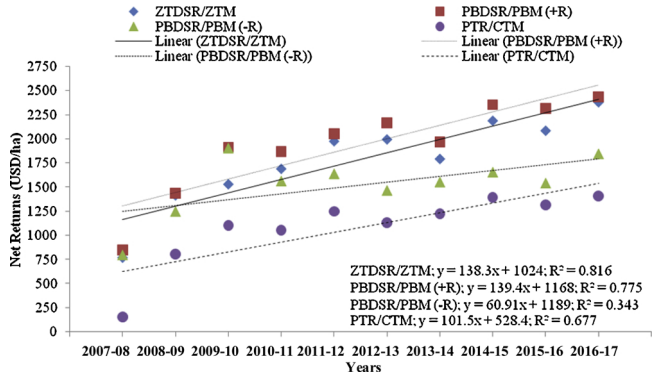

Fig. 6. Rice-maize system net returns over the years under different tillage and residue management practices.

system without residue retention. The findings of increased system productivity under CA with residue retention in our study are in agreement with the results obtained by other researchers (Jat et al., 2013, 2014). The four TCE and residue management practices analysis with APSIM using long term climatic data (1991–2017) after the calibration of model with two years observed records under given set of soil, climate and the crop variety. The simulations showed that across the years the rice yield was not much influenced among the different TCE and residue management practices. However, the maize yield was significantly affected by different TCE and residue management practices and remained sustainable under PBDSR/PBM (+R) and ZTDSR/ZTM treatments. The predicted mean variance of maize yield was smaller for CA-based PBM (+R), ZTM, and PBM (-R) practices and maximum for CTM suggesting that CA could be regarded superior and sustainable for long term yield goals while CT could be risky among different TCE and residue management practices (Ngwira et al. (2014), also found that the predicted mean variance of maize productivity was smaller for CA and maximum for CT system. This clearly shows the benefit of CA adoption in complete package rather than the adoption of its components in isolation only. The results of this trial also suggest that location specific adaptations of component technologies are critical for realizing the higher and sustainable benefits of the knowledge-intensive CA-based management systems.

4.2. Water-use and water productivity

The results of our study explicitly indicate that the CA-based-PB and PB-R treatments had 15.0–21.8% less water requirement compared to conventional till based PTR/CTM treatment. Application of water for crop production was lowest in PB plots due to lower supply requirement of irrigation water in furrows and higher infiltration opportunity time in flood irrigation system (Aggarwal and Goswami, 2003; Jat et al., 2013). Further, the use of furrows/beds hastens the speed with which irrigation water reaches the other end of the field and thus reduces irrigation amount, as the furrows occupy less than half the area of the field (Kukal et al., 2010). In all the years of study RM system, WP was significantly higher with CA-based PB plots (6.1–14.1 kg/ha-mm) followed by CA-based ZT plots (6.0–12.4 kg/ha-mm) compared to CT-based PTR/CTM plots. Further, the retention of residue at the surface in CA-based ZT and PB system helped in reducing the losses through evaporation and hence conserving soil moisture. Higher soil moisture in the seed-zone not only gave better crop growth but also increased crop WP (Parihar et al., 2016b, 2017a). Better water management under ZT and PB compared to CT-based plots increased the seed-zone moisture and favourable soil environment and, thus, it resulted in increase in RM

Table 5
Grain yield and net return advantage (± S.E.) under different components of CA in rice, maize and rice-maize system (comparison of ten years values).

Particulars	Treatment comparison	Additional yield (Mg/ha)			Additional net income (USD/ha)		
		Rice	Maize	RM system	Rice	Maize	RM system
Double ZT(+R) system as compared to absolute conventional system	(ZTDSR/ZTM)-(PTR/CTM)	0.01 ± 0.08	2.10 ± 0.22	2.15 ± 0.25	215 ± 16	481 ± 44	699 ± 50
Double PB(+R) system as compared to absolute conventional system	(PBDSR/PBM(+R)-(PTR/CTM)	0.14 ± 0.05	2.59 ± 0.18	2.77 ± 0.19	275 ± 14	570 ± 39	848 ± 45
Advantage of residue retention on double ZT system compared to double PB system	(ZTDSR/ZTM)-(PBDSR/PBM(-R)	0.29 ± 0.18	1.50 ± 0.36	1.78 ± 0.50	16 ± 39	248 ± 65	261 ± 96
Advantage of residue retention on double PB system	(PBDSR/PBM(+R)–(PBDSR/PBM(-R)	0.42 ± 0.17	1.99 ± 0.33	2.40 ± 0.45	76 ± 33	336 ± 60	411 ± 87
Advantage of tillage elimination in rice and maize crops	(PBDSR/PBM(-R)-(PTR/CTM)	−0.28 ± 0.16	0.60 ± 0.23	0.37 ± 0.37	199 ± 33	233 ± 34	437 ± 56

system grain yield with lesser water consumption. Balwinder-Singh et al. (2015), in a simulation study, have shown that CA practices along with sowing short duration rice varieties resulted in reduced ET and better soil moisture utilization. Similarly, Jat et al. (2013) reported the enhanced water productivity in CA-based management practices over CT and a mixture of CA and CT (i.e. CA without residue). The higher yield advantage during low rainfall years (2009-10 and 2015-16) further supports the assumption of better soil moisture environment in CA-based management practices (Govaerts et al., 2007; Thierfelder and Wall, 2010).

4.3. Economics

In our study; RM production rotation under CA-based ZT/PB systems incurred 922–1462 US$/ha/year, whereas conventional till based PTR/CTM system incurred 1180–1728 US$/ha/year (Table 4). These savings in cost of production were mainly due to non-requirement of preparatory tillage, unlike CT where 4–5 preparatory tillage operations were performed before rice transplanting and wheat seeding (see Section 2). Gathala et al. (2011a) reported about 79–95% reduction in tillage and crop establishment costs under ZT direct seeded system than in CT-based system. In RM system, the net returns were always significantly higher in CA-based ZT and PB systems than in CT based systems (Table 4 and Fig. 6). The net returns from RM system obtained in our study were slightly lower than that reported in rice-wheat system by Gathala et al. (2013) from North-Western IGP which may be due to higher productivity of rice and wheat. Our 10-year result indicated that just eliminating tillage in both rice and maize crops under RM system will offer an additional benefit of 215,481 and 699 US$/ha/year compared to absolute conventional system (PTR/CTM) in rice, maize and RM system, respectively (Table 5). In agreement with our findings, increased system productivity and economical profitability of rice–-wheat system with CA-based ZT/PB has also been reported by other researchers (Saharawat et al., 2010; Gathala et al., 2013; Jat et al., 2014). Similarly, eliminating tillage in both rice and maize under RM rotation gave additional net return 437 US$/ha/year over conventional tillage based RM rotation primarily due to increased yield (Tables 2 and 4). Increased in RM system productivity (REY) due to eliminating tillage in both the crops can be attributed to better germination, rooting and establishment of both the crops (Talukder et al., 2008). In both rice and maize adopting ZT and PB would provide additional RM system net return by 699 and 848 US$/ha/year over absolute CT-based system, respectively. PB combined with residue retention, would provide the additional system net returns by 411 US$/ha/year over production cost of RM system in PB without residue retention (Table 5). Double ZT systems (zero tillage in both crops) with retention of crop residue would offer additional system net returns benefit of 261 US$/ha/year from RM system over production cost of RM system in PB without residue retention (Table 5).

5. Conclusions

In a resource constrained smallholders dominated and highly climate vulnerable eastern IGP, results from 10-year of RM production system indicated that, CA-based management practices (PB and ZT) are more productive (on a system basis) compared to CT-based system. Also, CA practices with residue retention provide resilience for erratic rainfall conditions as observed by lowest decline in system productivity under PB and ZT compared to CT. APSIM simulation on the effect of various TCE and residue management practices on productivity of rice and maize, suggested that CA-based management practices are superior and sustainable for long term yield goals, while CT based practices could be the risky. Total water-use (irrigation + effective rainfall) of RM system was 10.6 to 21.8% lower under PB and ZT compared to CT, respectively. System water productivity increased by 27.1–57.4% and 39.4–68.3% under CA-based PB and ZT plots provided US$ 426–972 and 629–1028 /ha/year higher net returns (over variable cost) compared to CT, respectively. Our study reveals that CA-based management (ZT and PB with partial residue retention) in RM production system provides a potential option for producing more with less to meet future food needs and farm income on a sustainable basis to support resource poor farmers of Eastern IGP. The potential benefits of CA-based management practices in R-M system in long-term with less vulnerability to climate and high yields can only be realized with systems' approach. However, further research on component management practices (genotype selection, precision water and nutrient management, etc) for local adaptation of basic elements of CA is critical for large-scale adoption and long-term impact of CA-based systems.

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